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Analysis of the National Transonic Facility Mishap

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SUMMARY

The nonlinear dynamic finite element code DYnamic Crash Analysis of STructures DYCAST was used to model an accident scenario that occurred at the National Transonic Facility (NTF) wind tunnel. A post mishap investigation revealed that a total of 5 upstream bulkhead fairing plates were missing, three in one location and two in another. These plates were drawn into the wind tunnel's composite fan blades causing extensive damage. A DYCAST model was developed to determine if one-half of a small thermal shield flange clamp, weighing approximately 2.7 lbs, could have spun off the NTF drive shaft and impacted the bulkhead fairing plates with sufficient energy to cause failure of the attachment bolts. The clamp was presumed to have spun off at a tangent from the NTF drive shaft at a velocity of 1624 in/sec (drive shaft rotating at 580 rpm). The DYCAST analytical model predicts that impact of the 2.7 lbs projectile failed all of the bolts in two of the fairing plates allowing them to escape from the bulkhead ring with a low velocity of a few in/sec.

INTRODUCTION

The Landing and Impact Dynamics Branch (LIDB) at NASA Langley Research Center (NASA LaRC) has had an ongoing program for over 15 years of analytically and experimentally studying the effects of impact to aircraft and aerospace structure, including both metallic and advanced composite materials (ref.1). Consequently, after the National Transonic Facility (NTF) mishap, LIDB personnel and support contractors were contacted by the NTF Mishap Investigation Board to perform a nonlinear dynamic finite element analysis of a possible accident scenario. This involved the impact of various projectiles that could have been spun off from the NTF drive shaft onto the ring of bulkhead fairing plates that are mounted to the 15 feet diameter rim of the upstream nacelle bulkhead. A model consisting of three of the 35.75 x 8.125 x 3/8 inch thick curved aluminum bulkhead fairing plates was constructed using the nonlinear dynamic finite element code DYCAST (ref. 2).

DYCAST FEATURES

DYCAST is a nonlinear structural dynamic finite element computer code developed by Grumman Aerospace Corporation as part of the combined NASA/ FAA program for aircraft crashworthiness (ref. 3). It has been used extensively to model numerous structural impact problems such as full-scale transports (Boeing 720) (ref. 4) and transport sections (Boeing 707) (ref. 5), the Space Shuttle Orbiter skin panels under simulated hydrodynamic loads (ref. 6), crashworthy energy absorbing aircraft seats (ref. 7), and impacts of composite beams and frames (refs. 8-9). The element library consists of the following elements: 1) stringers (rods), 2) beams with axial, shear, torsional, and bending stiffnesses, 3) membrane skin triangles with inplane stiffness only , 4) three-node plate (shell) triangles with membrane and out-of-plane bending stiffnesses, 5) various nonlinear springs including contact elements, torsional, and ground springs.

Changing stiffnesses in the structure are accounted for by plasticity (material nonlinearity) and by large deflections (geometric nonlinearities). Material nonlinearities are accommodated by one of three options: 1) elastic-perfectly plastic, 2) elastic-linear hardening plastic, or 3) elastic-nonlinear

hardening plastic of the Ramberg-Osgood type. (For the NTF plate impact problem, the first option of elastic-perfectly plastic was chosen for simplicity.) Geometric nonlinearities are handled in an updated Lagrangian formulation by reforming the structure into its deformed shape after small time increments while accumulating deformations, strains, and forces. The nonlinearities due to combined loadings, such as beam-column effects, are maintained and the stiffness variation due to structural failures are computed. Failure of an element can be set to occur automatically when the specified material failure strains are exceeded. A partial failure criteria is used such that elements with more than one integration point through the cross section fail completely only when all integration point strains have exceeded the specified failure strain.

A restart feature permits a large problem, or one of long event duration, to be run as a sequence of smaller time segments. Other features include multiple load histories to subject the structure to time dependent loading; gravity loading; initial conditions including initial velocity, pitch, roll, and yaw; a bandwidth optimizer as a preprocessor; and deformed plots and graphics as postprocessors.

Both explicit and implicit time integrators are available and both static and dynamic problems may be run. The integrators available are central difference, modified Adams, Newmark-beta, and Wilson-theta.

IMPACT SCENARIO

A total of five bulkhead fairing plates were found to be missing after the mishap. Two adjacent plates were missing in one area and three adjacent plates were missing in another. From the evidence collected, including a footprint on a fairing plate that geometrically matched the smaller clamp, it was hypothesized that the thermal shield retainer clamps could have been spun off the NTF drive shaft, impacted the plates in at least two locations, and imparted sufficient energy to break all the bolts and dislodge the plates which were then drawn into the composite fan blades producing the resulting damage.

The scenario modeled with DYCAST is the impact by a projectile assumed to be 1/2 of the smaller clamp, weighing 2.704 lbs, onto three bulkhead fairing plates. Assuming the drive shaft was rotating at 580 rpm and the radius of the shaft is 26.75 inches, the velocity of the projectile would be 135.4 ft/s or about 1624 inches/s. From the geometry of the shaft and the surrounding ring of fairing plates, it can be shown that the clamp would be thrown off at a tangent to the shaft and would strike the fairing plates at approximately 17.3 degrees to the normal line to the fairing plate.

Some insight into the problem can be obtained from a consideration of the energy involved. The breaking load of the 3/8 inch diameter aluminum bolts was found to be approximately 5000 pounds. Assuming a bolt length of 1 inch and a failure strain of 5 %, about 250 in-lb of energy is required to break one bolt if the material is modeled as elastic-perfectly plastic. Thus to break all ten bolts in a fairing plate would require 2500 in-lbs of energy. The kinetic energy of a one pound object traveling 1624 in/s is more than 3400 in-lb which is sufficient energy to lift one plate if it is completely transferred to the bolts upon impact.

MODEL DESCRIPTION

A DYCAST finite element model was constructed representing three of the curved 35.75 x 8.125 x 3/8 inch thick 5083-0 aluminum bulkhead fairing plates that are spaced with a 1/8 inch gap between each plate. Each plate is bolted to the outer rim of the 15 foot diameter 2 1/2 inch wide bulkhead ring with six 2024-T4 aluminum 3/8 inch diameter bolts. The plates extend in a cantilever fashion by 5 5/8 inches beyond the edge of the rim and are connected together with 6 x 3 3/8 x 3/8 inch thick 5083-0 aluminum splice plates. Each splice plate requires four more 2024-T4 aluminum 3/8 inch diameter bolts to attach the two adjacent fairing plates together. Thus there are a total of 10 bolts in each fairing plate; 6 along the bulkhead rim and 2 at each end to attach to the splice plates.

Figure 1 shows the discretization of a single bulkhead fairing plate into 112 triangular 3-node shell elements. The three plate model (figure 2 - 3) had a total of 340 triangular shell elements: 336 triangular shell elements for the three fairing plates plus two additional elements for each of the two

splice plates. The ten aluminum bolts in each fairing plate were represented by circular cross-section beam elements. The beams representing the six bolts that attached each fairing plate to the rim of the bulkhead ring had their lower end (the end in the bulkhead ring) degrees of freedom fixed. The bolts in the splice plate were represented by beams that connected the fairing plate shell elements to the splice plate shell elements. A total of 32 beam elements were used in the three plate model. To represent the rim of the bulkhead ring, 24 contact elements were needed (see figure 4). These are compression-only springs that prevent the fairing plates from entering the rim but allow them to lift off once the fasteners fail. The model had a total of 1165 degrees of freedom. Material properties for the two aluminum alloys are shown in Table 1. The materials were assumed to be elastic up to yield stress and then perfectly plastic until failure. The failure strain for the aluminum 2024-T4 bolts was assumed to be 5 %. The failure strain of the 5083-0 aluminum of the fairing plates was assumed to be 10 %. The density of the aluminum was input as 0.096 pounds per cubic inch.

To model the impact of the 2.704 pound clamp, the mass of the clamp was divided into two equal parts, lumped at nodes 81 and 96, and given an initial velocity of 1624 in/s at 17.3 degrees to the normal of the second fairing plate (plate 2 in figure 2). The position at nodes 81 and 96 corresponds to the position of the actual footprint observed post mishap. These nodes are approximately halfway between the second and third bolts that fasten the plate to the bulkhead ring. Also note from figure 2, the origin of the global axis system used in DYCAST is located at the center of the bulkhead ring diameter, and the global Z-axis passes through the outer edge of the third plate at its centerline.

The implicit variable time step Newmark-beta integrator was used with 0.00005 second as the initial time step. A bandwidth optimizer was used as a preprocessor. The structural mass matrix was calculated using a consistent mass approach with the lumped nodal masses of the projectile (a diagonal matrix) added to the structural mass matrix. The coefficient matrix, which is a combination of the mass and stiffness matrices for the implicit method, was reformed at every time step. This technique required over 12 cpu hours on a microVax computer to run to 0.015 seconds in real time.

RESULTS

Figures 5 - 8 illustrate graphically the effects of the impact of the 2.704 pound projectile onto the second bulkhead fairing plate. Figure 5 shows the impact point on the second plate and the deformed shape at approximately 0.0005 seconds. The bolt to the left of the impact point failed first and the bolt to the right of the impact point failed 0.0001 seconds later. In figure 6, at approximately 0.0016 seconds after impact, the locations of bolt failures three through eight are shown with the exact time of failure for each bolt given in parentheses. Figure 7, at 0.003 seconds after impact, shows that the last bolt in the splice plate at the left end of plate 2 has failed. At this time the second plate is free from the left splice plate and all bolts along the bulkhead rim have failed. The plate continues to lift up and starts pulling the third fairing plate loose also. By 0.015 seconds after impact (figure 8), all the bolts have failed in both the second and third fairing plates and the bolts in the right splice plate have failed also. The slanted heavy lines in this figure show the path of the failed beams (bolts). Also, by this time , the initial velocity of 1624 inches/second at nodes 81 and 96 (the impact point) has been reduced to just a few inches per second. The majority of the kinetic energy of the impacting projectile was converted into nonrecoverable strain energy (plastic deformation of the fairing plates and bolts.)

CONCLUSIONS

An accident scenario of the NTF mishap was modeled using the DYCAST nonlinear finite element code. The analysis showed that impact by one half of a small thermal shield flange clamp onto three bulkhead fairing plates was sufficient to dislodge two of the fairing plates allowing them to travel downstream into the tunnel fan blades producting extensive damage to the facility. It is reasonable to conclude that if a larger mass, such as the complete clamp assembly or parts of a larger clamp assembly, were considered even more damage would have occurred.

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TABLE 1

MATERIAL PROPERTIES USED IN DYCAST MODEL

Materials assumed to be elastic-perfect plastic

FAIRING PLATE (Aluminum 5083-0)

Young's Modulus	10.3 million psi
Poisson's ratio	0.3
Yield stress	35000 psi
Yield strain	.003
Failure strain	.10

BOLTS (Aluminum 2024-T4)

Young's Modulus	10.3 million psi
Poisson's ratio	0.3
Yield stress	69900 psi
Yield strain	.006
Failure strain	.05

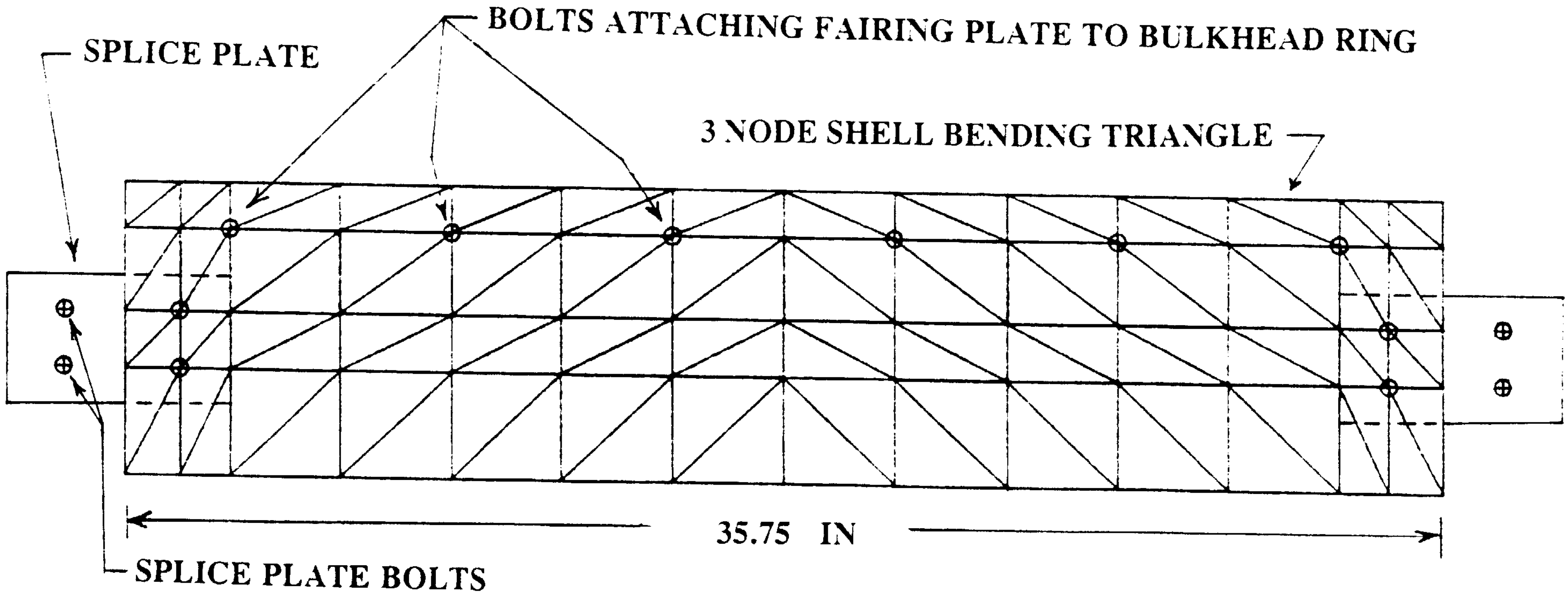


Figure 1. A single fairing plate showing spacial discretization, bolt locations, and splice plates.

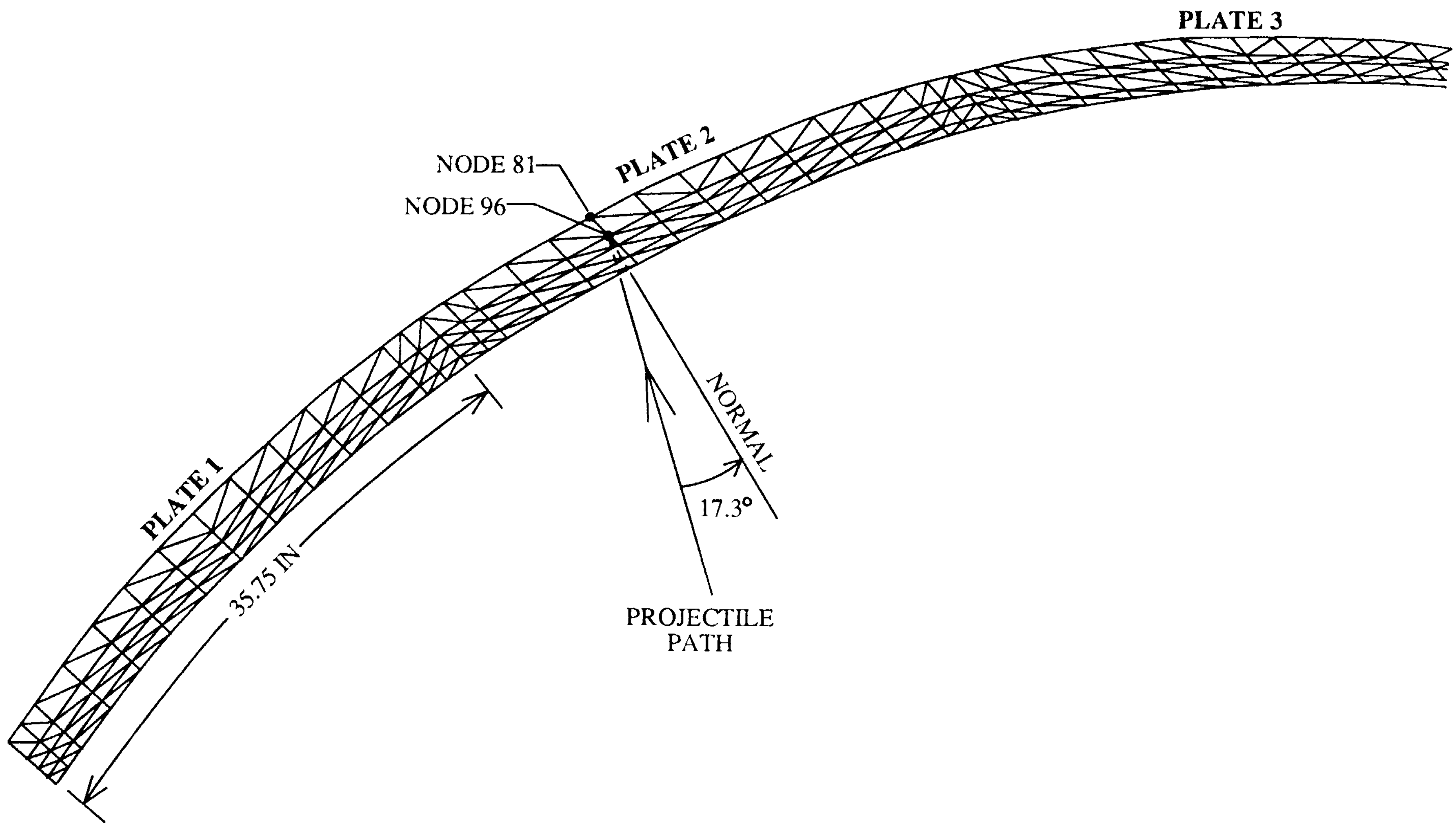
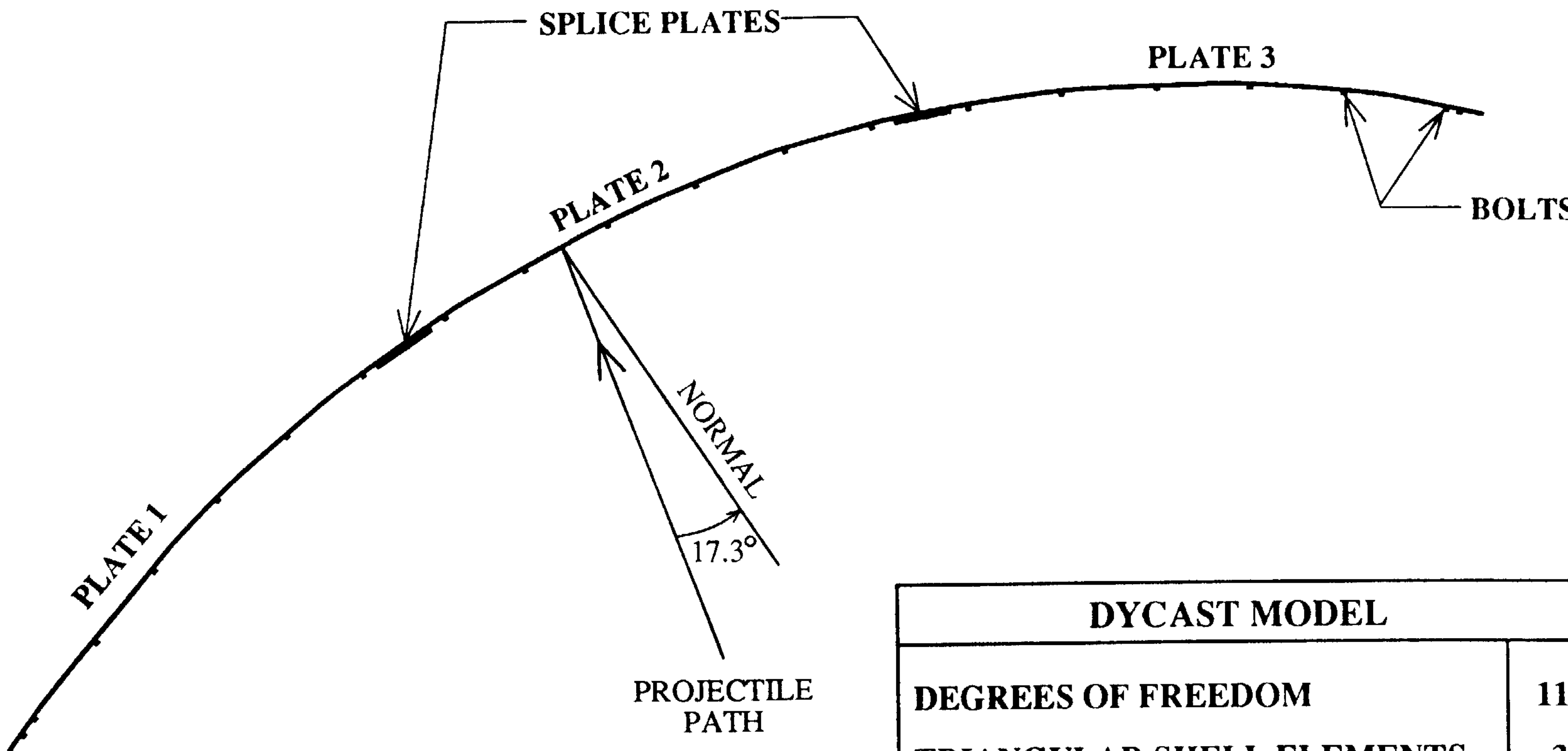


Figure 2. Three plate DYCAST model showing projectile path and 2.704 lb projectile lumped at nodes 81 and 96.



DYCAST MODEL	
DEGREES OF FREEDOM	1165
TRIANGULAR SHELL ELEMENTS	340
BEAM ELEMENTS	32
CONTACT ELEMENTS	24

Figure 3. Edge on view of three-plate DYCAST model showing location of splice plates and listing number of elements

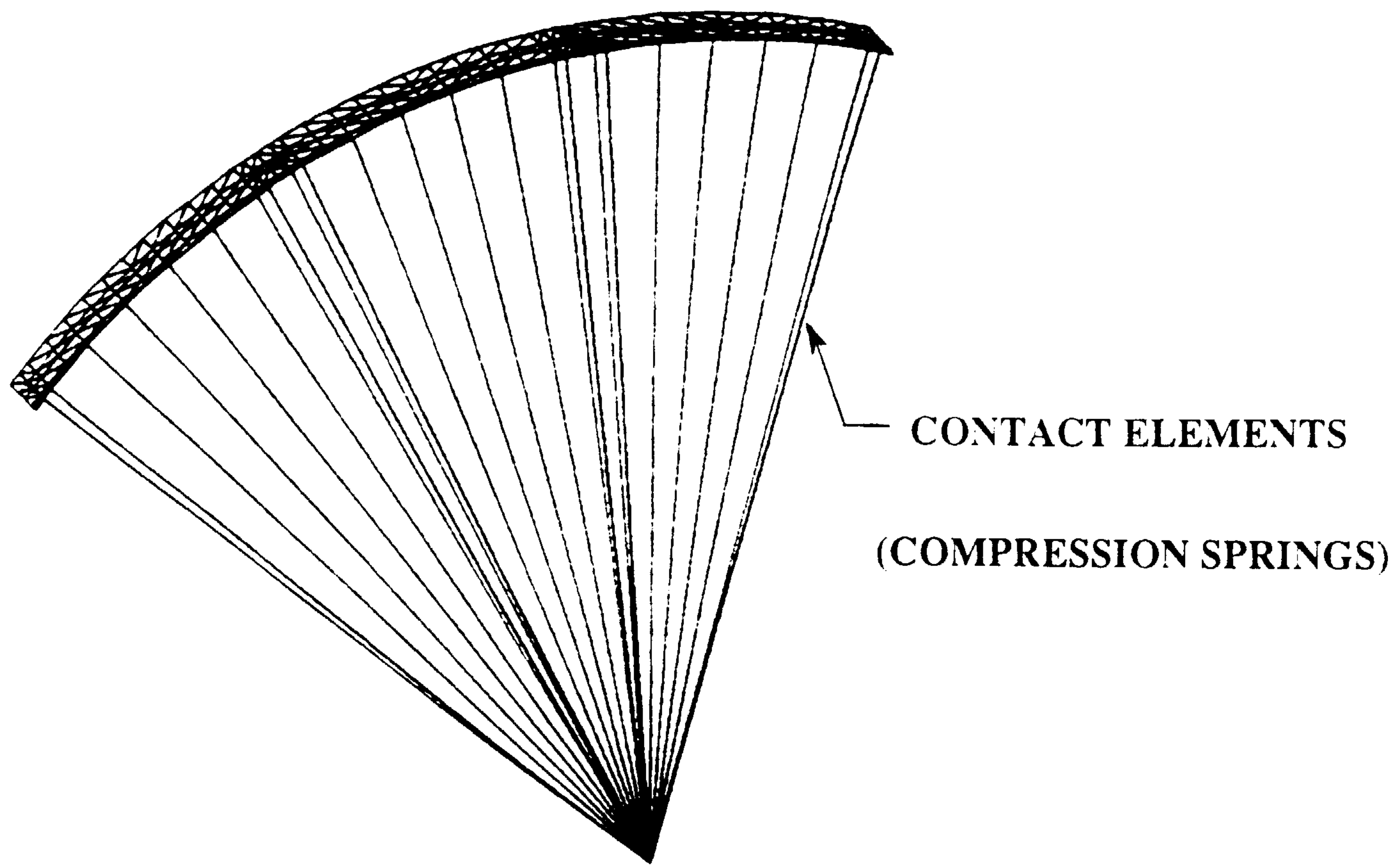


Figure 4. Three plate DYCAST model illustrating the 24 contact springs that represent the surface of the bulkhead ring.

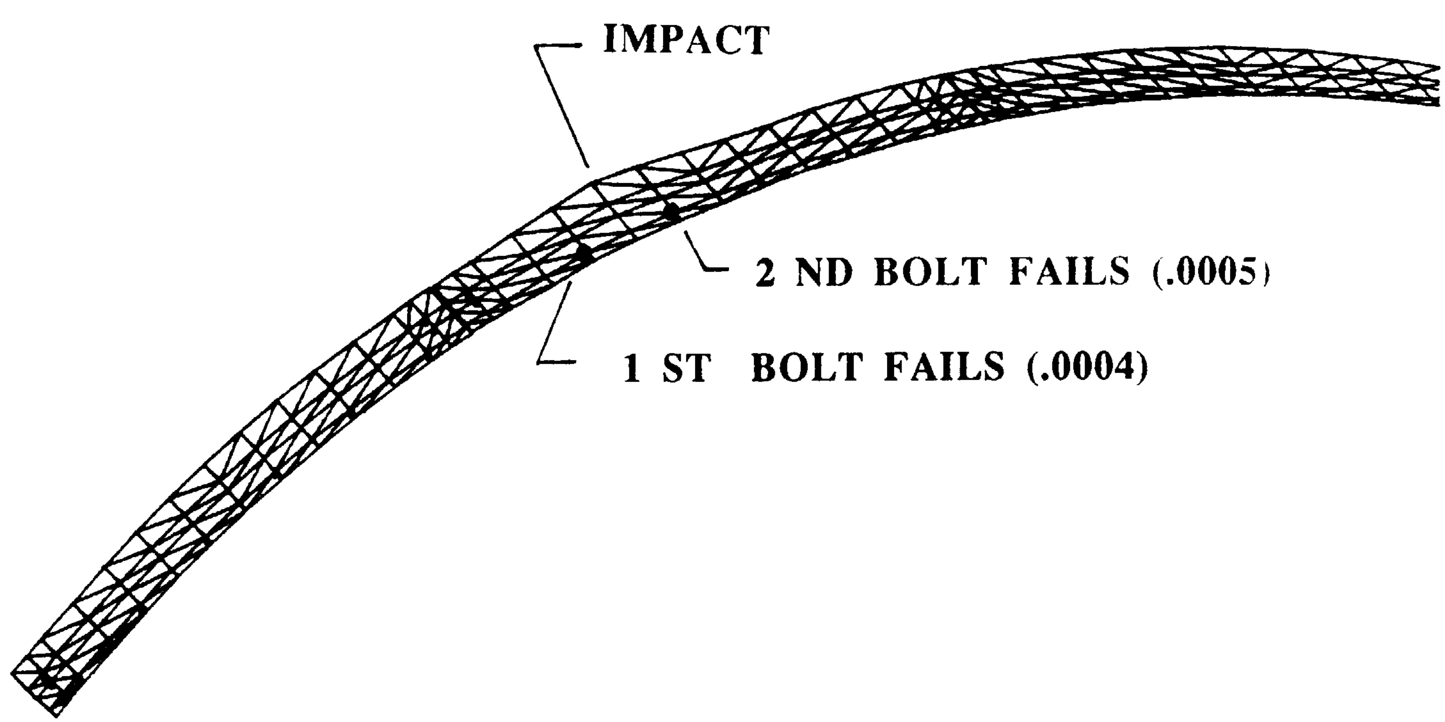


Figure 5. The model approximately 0.0005 seconds after impact showing the locations of the first two bolt failures. The number in parentheses is the time after impact that the failure is predicted by the model.

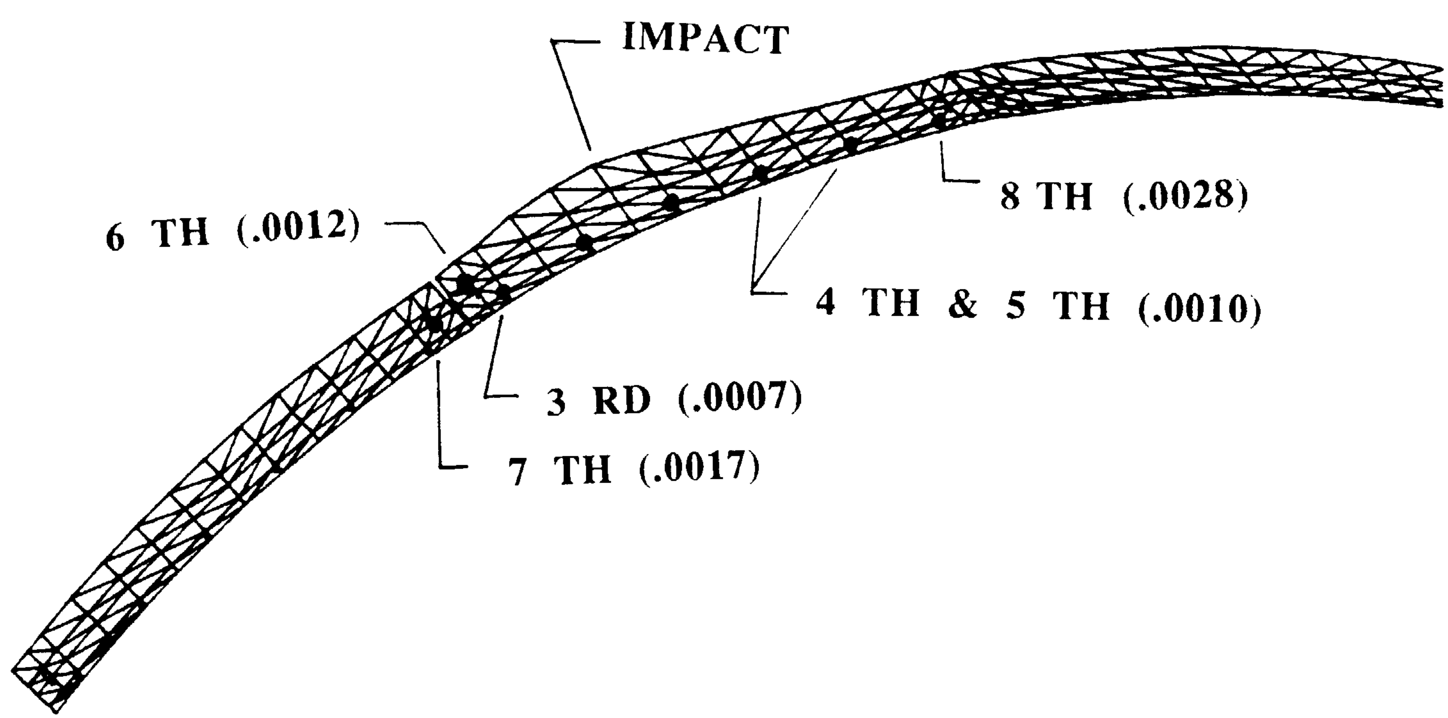


Figure 6. The model approximately .0016 seconds after impact with locations and times for bolt failures 3 through 8. Note the seventh failure was in the splice plate on the first plate.

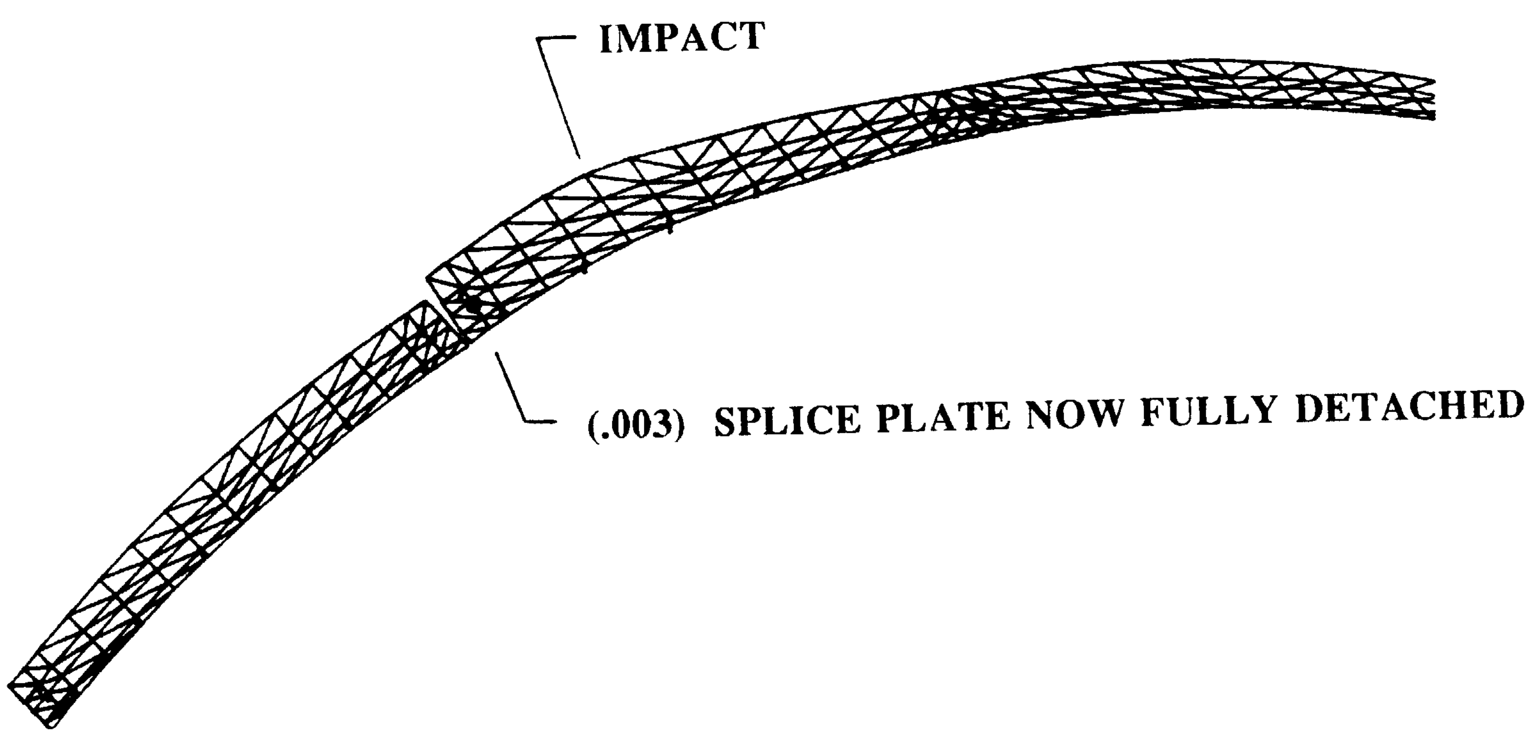


Figure 7. The second plate becomes fully free from the bulkhead ring at 0.003 seconds. The last bolt in the left splice plate has broken, but the bolts in the right end splice plate are still holding.

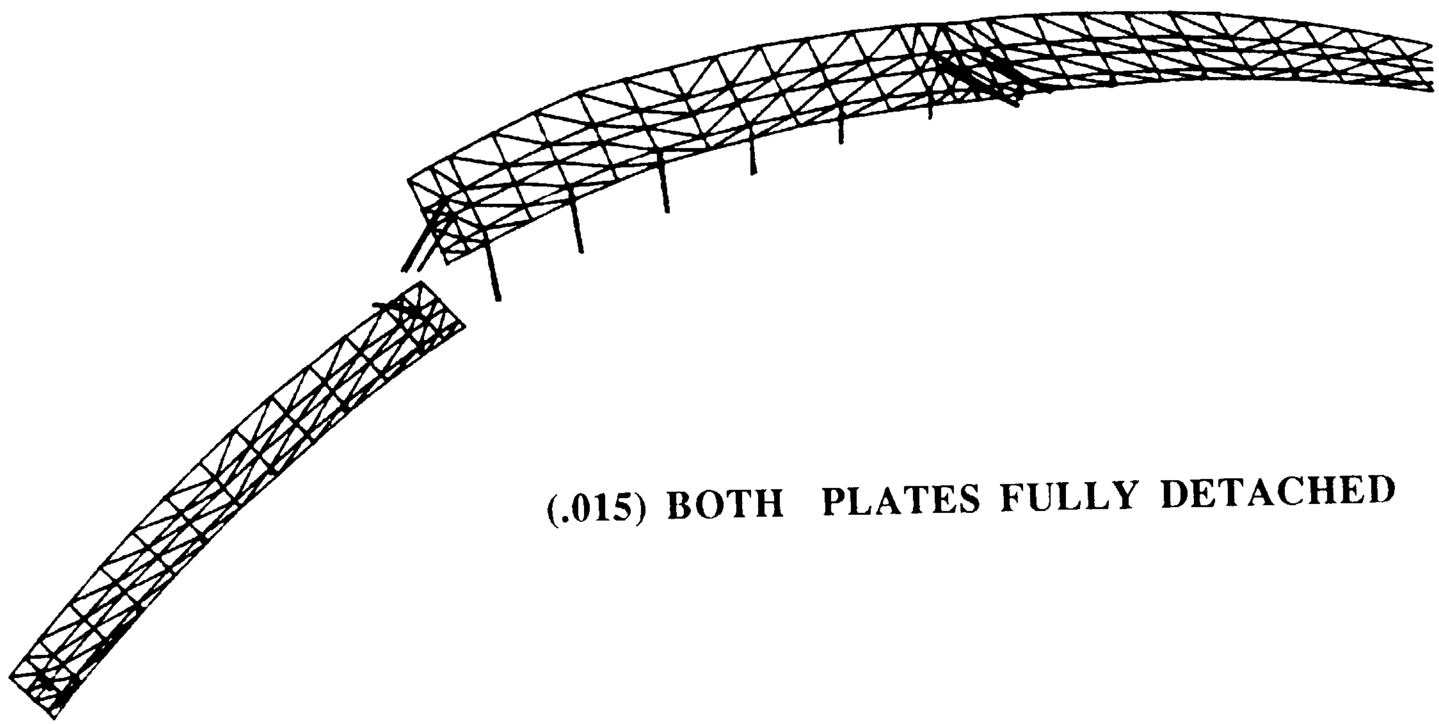


Figure 8. By time 0.015 seconds both the second and third plates have lifted off from the bulkhead ring. The slanted heavy lines are from the failed beam elements (bolts).

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16. Abstract

The nonlinear dynamic finite element code DYnamic Crash Analysis of STructures (DYCAST) was used to model an accident scenario that occurred at the National Transonic Facility (NTF) wind tunnel. A post mishap investigation revealed that a total of five upstream bulkhead fairing plates were missing, three in one location and two in another. These plates were drawn into the wind tunnel's composite fan blades causing extensive damage. A DYCAST model was developed to determine if one-half of a small thermal shield flange clamp, weighing approximately 2.7 lbs., could have spun off the NTF drive shaft and impacted the bulkhead fairing plates with sufficient energy to cause failure of the attachment bolts. The clamp was presumed to have spun off at a tangent from the NTF drive shaft at a velocity of 1624 in/sec (drive shaft rotating at 580 rpm). The DYCAST analytical model predicts that impact of the 2.7 lbs. projectile failed all of the bolts in two of the fairing plates allowing them to escape from the bulkhead ring with a low velocity of a few in/sec.

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